The Role of the Voltaic Pile in the Galvani-Volta Controversy Concerning Animal *vs.* Metallic Electricity

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THE striking effects of electricity on animals and human subjects had been studied for more than half a century before Luigi Galvani startled the scientific world in March 1791 with his famous treatise, 'Commentary on the Effects of Electricity on Muscular Motion.'[1] A reflection of this activity is seen in the fact that twenty-six articles or reviews of books on medical electricity, describing attempts to use electric currents to excite limbs in paralytic patients, appeared between 1750 and 1780 in France alone in the *Journal de Médecine*.[2]

In the 'pre-Galvani' period of electrophysiology static electric machines and huge Leyden jars provided the source of transient electric currents for the serious investigation of excitability in living systems. Indeed the rise of the science of electricity, to which Benjamin Franklin so richly contributed, was overwhelmingly important for the emergence of electrophysiological investigations. Even by 1750 extensive investigations of electrical phenomena had produced a substantial body of experimental facts and a theory of the 'electric fluid' which experimentalists, by various techniques, were able to generate, conduct, and store, in Leyden jars, for example.[3] Thus, long before Galvani's work, electrical phenomena had become almost a commonplace, at least in the various centers of learning.

However, electricity, a 'subtle' and 'weightless fluid,' appeared to have imponderable properties and indeed was manifested only by the remarkable effects it produced. Therefore, it should not surprise even the most

1. Luigi Galvani, *De viribus electricitatis in motu musculari commentarius* (Bologna, 1791).
2. Hebbel E. Hoff, 'Galvani and pre-Galvanian electrophysiologists,' *Ann. Sci.*, 1936, *10*, 163.
3. J. B. Priestley, *The history and present state of electricity*, 2nd ed. (London, 1769).

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casual reader of the pertinent literature that the concept of the electric fluid gradually became associated by some natural philosophers with the already prevalent idea of a 'nervous fluid' which was believed to be secreted by the brain and conducted throughout the organism via the nerve pathways. Thus, when Galvani began his investigations a decade or more before his publication of 1791, physiologists and scholars from various fields were espousing somewhat confusing and nebulous hypotheses of the role of 'animal electricity' in the nerves and muscles of the living organism. In Galvani's Commentary the scientific world saw for the first time a series of elaborate experiments on the effects of electric discharge derived from 'atmospheric electricity,' static electric machines, and Leyden jars. One particular observation proved to be unexpected and it clearly set the stage for the momentous developments that were to come. Galvani, in Part III of the Commentary, describes how he made his discovery:

Since I had upon occasion remarked that prepared frogs, which were fastened by brass hooks in their spinal cord to an iron railing which surrounded a certain hanging garden of my home, fell into the usual contractions not only when lightning flashed but even at times when the sky was quiet and serene, I surmised that these contractions had their origin in changes which occur during the day in the electricity of the atmosphere. Hence with confidence I began diligently to investigate the effects of these atmospheric changes on the muscular movements I witnessed and I repeated the experiment in various different ways. Therefore at different hours and for a span of many days I observed the animals which were appropriately arranged for this purpose, but scarcely any motion was evident in their muscles. I finally became tired of waiting in vain and began to press and squeeze the brass hooks which penetrated the spinal cord against the iron railing. I hoped to see whether muscle contractions were excited by this technique and whether they revealed any change or alteration. As a matter of fact, I did observe frequent contractions but they had no relation to the changes in the electrical state of the atmosphere.

Now since I had observed these contractions only in the open air and had not yet carried out the experiment elsewhere, I was on the point of postulating that such contractions result from atmospheric electricity slowly insinuating itself in the animal, accumulating there, and then being rapidly discharged when the hook comes in contact with the iron railing. For in experimenting, it is easy to be deceived and to think we have seen and detected things which we wish to see and detect.

But when I brought the animal into a closed room, placed it on an iron plate, and began to press the hook which was fastened in the spinal cord against the plate, behold!, the same contractions and movements occurred as before. I im-

mediately repeated the experiment in different places with different metals and at different hours of the day. The results were the same except that the contractions varied with the metals used; that is, they were more violent with some and weaker with others. Then it occurred to me to experiment with other substances that were either non-conductors or very poor conductors of electricity, like glass, gum, resin, stones, and dry wood. Nothing of the kind happened and no muscular contractions or movements were evident. These results surprised us greatly and led us to suspect that the electricity was inherent in the animal itself. An observation that a kind of circuit of a delicate nerve fluid is made from the nerves to the muscles when the phenomenon of contractions is produced, similar to the electric circuit which is completed in a Leyden jar, strengthened this suspicion and our surprise.[4]

This striking observation was interpreted by Galvani as evidence of internal electricity, 'animal electricity.' He inferred that since the contraction of muscle occurred without the application of an electrical discharge from an external source, i.e., lightning or static electric machine, the source must be internal. In Galvani's view the external arc of conductors played a passive role in providing a pathway for electricity to flow from nerve to muscle.

Scholars far and wide became fascinated with Galvani's finding and seemed to accept his interpretation. Many decades of speculation about the existence of electricity within the nerve pathways appeared to be confirmed in a well-defined experimental situation. Galvani apparently had demonstrated that electric fluid existed within nervous tissue and that it could, under certain conditions, discharge into muscle, causing it to contract.

The experiment using the frog's legs and an external arc of metals was repeated and discussed within a short time by countless enthusiasts and particularly attracted the attention of the physicist, Alessandro Volta, who had already established himself as an outstanding investigator of electrical phenomena. Volta initially seemed to accept Galvani's view, which was that a current of animal electricity originated within the organism and was conducted from the nerve to the muscle via the external arc of metals. But Volta gradually became more interested in Galvani's observation that the vigor of the contractions depended on the kind of metal used to form the external arc. Galvani had noticed this, as is seen in the above quotation, but apparently dismissed it as unimportant. In a public lecture on 5 May

4. Luigi Galvani, *Commentary on the effects of electricity on muscular motion*, Margaret Glover Foley, trans. (Norwalk, Conn., Burndy Library, 1953), 176 pp. (pp. 59–60).

1792, within a year after publication of the Commentary, Volta criticized Galvani's interpretation of his original experiment, which we shall refer to as the 'experiment with dissimilar metals.' Volta, in *direct opposition* to Galvani, argued that the current did not arise within the organism. This sweeping assertion was a consequence of his demonstration that an arc of dissimilar metals in contact with fluid could generate an electric current.

Many letters and publications followed in which Volta explained that in Galvani's experiment the contraction was due to the electric current arising from the externalized metallic arc—'metallic electricity'—and that animal electricity was *not* involved. This is precisely what Volta wrote to Cavallo with remarkable lucidity in a letter[5] of 22 May 1793 that was read at the Royal Society on the following 5 December:

> . . . The name of animal electricity is by no means proper, in the sense intended by Galvani and by others, namely, that the electric fluid becomes unbalanced in the animal organs, and by their own proper force, by some particular action of the vital powers. No, this is mere artificial electricity induced by an external cause, that is, excited originally in a manner hitherto unknown, by the connexion of metals with any kind of wet substance. And the animal organs, the nerves and the muscles, are merely passive, though easily thrown into action, whenever, by being the circuit of the electric current, produced in the manner already mentioned, they are attached and stimulated by it, particularly the nerves.

Volta's *idée fixe* concerning the passivity of the biological system—reinforced by his assertion that the external arc of metals is the *sole* source of electricity—is the key to his subsequent illogical line of argument. This, as we shall see, persisted through the years and culminated in his famous letter of 1800 in which the 'Voltaic pile' was described for the first time. To most scholars this document constitutes the definitive judgment against animal electricity. It is noteworthy, however, that few historians have treated the letter explicitly with regard to the question, namely, did Volta's communication disprove Galvani's claim that he had shown the existence of animal electricity?

To appreciate fully the remarkable intellectual position taken by Volta and his followers throughout the period leading up to the letter, it should be noted that an unambiguous example of an electric current emanating from a biological organism had already been firmly established in the studies of electric fish carried out by several investigators. For example, the anatomy of the electric organ of the torpedo and its 'electric property'

5. Allesandro Volta, Letter printed in his *Opere* (Milano, 1918), 7 vols., I, 203–208.

were treated in two complementary papers by John Hunter[6] and John Walsh,[7] respectively, which appeared in the *Philosophical Transactions* in 1773. In the same journal two years later Williamson[8] contributed a paper on the electric eel, *Gymnotus*. In the Commentary, no reference is made to the above articles but Galvani discusses the 'electricity of the torpedo' as an explicit example of 'animal electricity.' Volta himself, as early as May 1782, in a letter[9] to Mme. Le Noir de Nanteuil, indicates that he was fully aware of the electric fishes:

> In order that we may be entitled to speak of *animal electricity*, we must find a kind of electricity essentially linked with life itself, and inherent in some animal function. Now, does such electricity really exist? Yes, it has been discovered in the *torpedo* and in the *electric eel* of Surinam, which after Linnaeus, Natural Philosophers call *Gymnotus electricus*. . . .

However, it is striking that in the years following Galvani's Commentary, except for a brief reference in 1792, Volta maintained strict silence on the subject of the electric organ. Instead we see only discussion of the frog's leg with its nerves and muscles, as in the above-mentioned letter to Cavallo. That a significant segment of the scientific community apparently accepted and reinforced Volta's intellectual position is reflected, for example, in the award of the Copley medal to Volta in 1794. On this occasion, in the address[10] by Sir Joseph Banks, President of the Royal Society, Volta was lauded for his 'infinite acuteness of judgment' in demonstrating that the external arc of metals generated the feeble electric current which excited the nerves owing to their 'excessive irritability' and that indeed metals were not 'mere agents in conducting the animal electricity,' as proposed by Galvani.

Let us turn now briefly to Galvani. It is quite clear that he accepted Volta's criticism because he proceeded to carry out an experiment without the arc of metals, the only logical experiment that could counter Volta's argument. The 'experiment without metals' was reported in 1794 in an

6. John Hunter, 'Anatomical observations on the torpedo,' *Phil. Trans.*, 1773, *63*, 478–489.

7. John Walsh, 'Of the electric property of torpedo: in a letter to Ben. Franklin,' *Phil. Trans.*, 1773, *63*, 461–477.

8. Hugh Williamson, 'Experiments and observations on the gymnotus electricus, or electric eel,' *Phil. Trans.*, 1775, *65*, 94–101. See also Alexander Garden, 'An account of the gymnotus electricus,' *Phil. Trans.*, 1775, *65*, 102–111.

9. Volta (n. 5), I, 8–12.

10. Bern Dibner, *Galvani-Volta. A controversy that led to the discovery of useful electricity* (Norwalk, Conn., 1952), pp. 25–26. (Excerpt from the address at the Anniversary Meeting of the Royal Society on 1 December 1794.)

anonymous tract, the *Trattato* and *Supplemento*,[11] which scholars have ascribed to Galvani. Confining his experiments to an arc consisting solely of tissue, namely, nerve and thigh and leg muscles, Galvani writes in the *Trattato*:

> Then let the natural parts of the thigh be touched, namely, either by raising the nerves with a non-conducting body and subsequently allowing them to fall freely on the thigh, or by pressing them with the said body into a loose contact, and, if possible, only towards one point on the muscle. When the contact is thus made muscle contractions . . . shall be seen to appear. . . . This experiment is crucial in my opinion.[12]

While he was not explicit about where in the arc of nerve and muscle tissue the electric current originated, Galvani had demonstrated that the contractions could occur without the agency of metals and thus had reinforced his original interpretation that animal tissue had the intrinsic property of generating electric current. It would appear that with this observation the lines were drawn, namely, some investigators supported Galvani's thesis of a general animal electricity while others opposed him, in agreement with Volta.

Galvani virtually withdrew from the arena, as evidenced by the fact that only two works are known to have appeared in the years remaining before his death in 1798: namely, a notebook ('Taccuino') in 1795—discovered posthumously many years later—in which he recorded his work on the electrical properties of torpedo, and a series of five memoirs[13] in 1797 on animal electricity dedicated to Spallanzani, the eminent zoologist. In the second memoir of the series a second experiment without metals is described, more refined than the first experiment of 1794. And in the last memoir, the fifth, he reports on his work with the electric organ of torpedo.

It seems inconceivable that Volta remained unchallenged in his dismissal of Galvani's experiments without metals, and in fact in 1797 we see the publication of a work describing experiments on nerve and muscle by the celebrated Alexander von Humboldt. In this treatise experiments are

11. [Luigi Galvani], *Dell' uso e dell' attività dell'arco conduttore nelle contrazioni dei muscoli* (Bologna, 1794). *Supplemento al trattato dell' uso e dell' attività. . . .* (bound with the Trattato). The translation used here is quoted from the paper by G. C. Pupilli and E. Fadiga, 'The origins of electrophysiology,' *J. World Hist.*, 1963, *7*, 547–589 (see p. 568).

12. See also J. F. Fulton and H. Cushing, 'A bibliographical study of the Galvani and the Aldini writings on animal electricity,' *Ann. Sci.*, 1936, *1*, 239–268 (pp. 245–246).

13. Luigi Galvani, *Memorie sulla elettricità animale—al celebre Abate Lazzaro Spallanzani. Aggiunte alcune elettriche esperienze di Gio. Aldini* (Bologna, 1797). Reprinted in *Opere edite ed inedite* (Bologna, 1841), pp. 299–434.

described demonstrating contraction in the nerve-muscle preparation without the external arc of metals—and independent confirmation of Galvani's 'experiment without metals.' Humboldt states his position vis-à-vis Volta quite clearly:

> [p. 367] My new experiments force me to declare myself the adversary of Volta. I shall employ in my refutation all the caution he merits; and I have a trust so limitless in the character of a man to whom truth is dear that I do not fear, in so doing, to lose his good will. [p. 373] The following facts are in evident contradiction with the theory of Volta:
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> . . . The very simple experiment, Fig. 3, explains this effect. When one cuts in a very-much-alive individual [frog] the portion x of the crural nerve, when one brings together immediately, with the aid of a tube of glass, this portion of nerve, the nerve itself and the muscle to which it is distributed, as soon as the contact is made there will be some contractions in the leg. Here there are absolutely only two heterogeneous substances, the nerve and the muscle. It is the same in Fig. 2 where x, y, and z are all three pieces of the same muscle. Yes! I have demonstrated that Galvanic phenomena take place without making use of different substances but merely by turning back a red, but not tendinous, portion of leg muscle against the sciatic nerve. In this case the chain consists only of organically united parts, the sciatic nerve and the muscle.[14]

Volta, however, remained adamant in refusing to accept these experiments, both Galvani's and Humboldt's, as proof of current arising from within the organism. He always managed to argue that the external arc, whether of metals in contact with liquids or liquids alone, contained the seat of the electric current. He was not cautious about the possibility of currents arising within the nerve-muscle system. Instead he persistently rejected inquiry into the biological organism.

While Volta might have been convinced of the soundness of his position in rejecting Galvani's experiments on the nerve-muscle preparation as evidence for animal electricity, the problem posed by the electric organ of torpedo must have been weighing on his mind, especially since he had acknowledged this source of animal electricity as early as 1782. Even to Volta it was unquestionably the clear-cut case of electricity arising from a biological organism.

The break in Volta's silence of many years on this point came most dramatically on 20 March 1800, when he sent a letter—in two parts—to

14. Alexander von Humboldt, *Versuche über die gereizte Muskel- und Nervenfaser nebst Vermuthungen über chemischen Process des Lebens in der Thier und Pflanzwelt* (Posen, 1797), 2 vols., I, 367 and 373.

Sir Joseph Banks of the Royal Society in London.[15] The letter was read before the Society on 26 June and published in the *Philosophical Transactions* in the original French. The English translation appeared in the *Philosophical Magazine*[16] later in the same year. The letter begins with an apology for not having communicated sooner his recent 'experiments on electricity excited by the mere mutual contact of different kinds of metal, and even by that of other conductors, also different from each other, either liquid or containing some liquid, to which they are properly indebted for their conducting power.' Volta then proceeds to describe a new apparatus:

> The apparatus to which I allude, and which will, no doubt, astonish you, is only the assemblage of a number of good conductors of different kinds arranged in a certain manner. Thirty, forty, sixty, or more pieces of copper, or rather silver, applied each to a piece of tin, or zinc, which is much better, and as many strata of water, or any other liquid which may be a better conductor, such as salt water, ley, &c., or pieces of pasteboard, skin, &c., well soaked in these liquids; such strata interposed between every pair or combination of two different metals in an alternate series, and always in the same order of these three kinds of conductors, are all that is necessary for constituting my new instrument, which, as I have said, imitates the effects of the Leyden flasks, ...

The second paragraph of Volta's letter contains the greatest surprise of all:

> To this apparatus, much more similar at bottom, as I shall show, and even such as I have constructed it, in its form to the *natural electric organ* of the torpedo or electric eel, &c. than to the Leyden flask and electric batteries, I would wish to give the name of the *artificial electric organ*: and, indeed, is it not, like it, composed entirely of conducting bodies? Is it not also active of itself without any previous charge, without the aid of any electricity excited by any of the means hitherto known? Does it not act incessantly, and without intermission? And, in the last place, is it not capable of giving every moment shocks of greater or less strength, according to circumstances—shocks which are renewed by each new touch, and which, when thus repeated or continued for a certain time, produce the same torpor in the limbs as is occasioned by the torpedo, &c?

The apparatus is presented to the world as a realistic model of the natural electric organ. He is concerned first with the geometrical shape of the

15. Alessandro Volta, 'On the electricity excited by the mere contact of conducting substances of different kinds,' *Phil. Trans.*, 1800, *90*, 403–431 (text in French). Reprinted in *Isis*, 1931, *15*, 129–159 (p. 127).

16. An English translation appeared with the same title in *Phil. Mag.*, 1800, *7*, 289–311. Reprinted in *Amer. J. Physics*, 1945, *13*, 397–406.

electric organ which, as he states further on in the letter, consists of 'membranes in the form of thin disks, which lie one above the other from the bottom to the summit of each column.'

The 'column,' the *artificial electric organ*, he constructs in the following manner:

> Having all these pieces ready in a good state, that is to say, the metallic disks very clean and dry, and the non-metallic ones well moistened with common water, or, what is much better, salt water, and slightly wiped that the moisture may not drop off, I have nothing to do but to arrange them, a matter exceedingly simple and easy. I place them horizontally, on a table or any other stand, one of the metallic pieces, for example one of silver, and over the first I adapt one of zinc; on the second place one of the moistened disks, then another plate of silver followed immediately by another of zinc, over which I place another of the moistened disks. In this manner I continue coupling a plate of silver with one of zinc, and always in the same order, that is to say, the silver below and the zinc above it, or vice versa, according as I have begun, and interpose between each of these couples a moistened disk. I continue to form, of several of these stories, a column as high as possible without any danger of its falling.

Much of this portion of the letter is devoted to describing the construction of 'my apparatus which is susceptible of several variations,' one of which he calls a 'chain of cups.'

Experiments are described in which the pile, 'the electromotive apparatus,' generates the electric current which 'excites not only contractions and spasms in the muscles, convulsions more or less violent in the limbs through which it passes in its course; but it irritates also the organs of taste, sight, hearing, and feeling, properly so called, and produced in them sensations peculiar to each.' It should be noted that Volta in previous communications had reported the effect evoked by relatively feeble continuous currents generated with single metallic arcs. He is now reporting on the effects due to augmentation of the stimulating current by arranging the arcs in series, effects which hitherto had been observed, even before Galvani's work, with sources of current provided by lightning, electrostatic machines, and Leyden jars ('flasks').

However, there is a new facet in this communication, namely, Volta is now explicitly concerned with the unambiguously proven source of 'animal electricity,' the *natural electric organ*. He has, so to speak, turned full circle by coming to grips with biological tissue and thus with Galvani's contention that the biological organism can generate electric current. And what is truly astonishing is the fact that he uses the metallic pile to explain

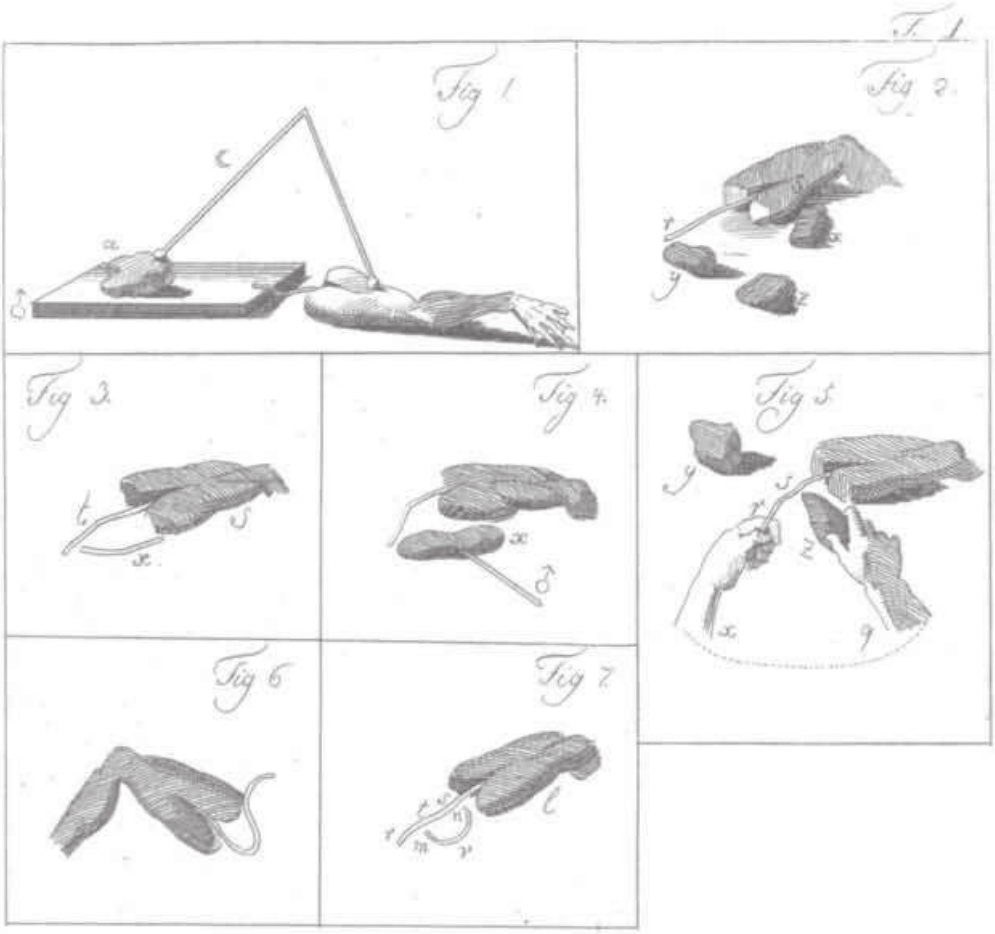

FIG. 1. Humboldt's illustration of his experiment without metals (n. 14, vol. II, 468).

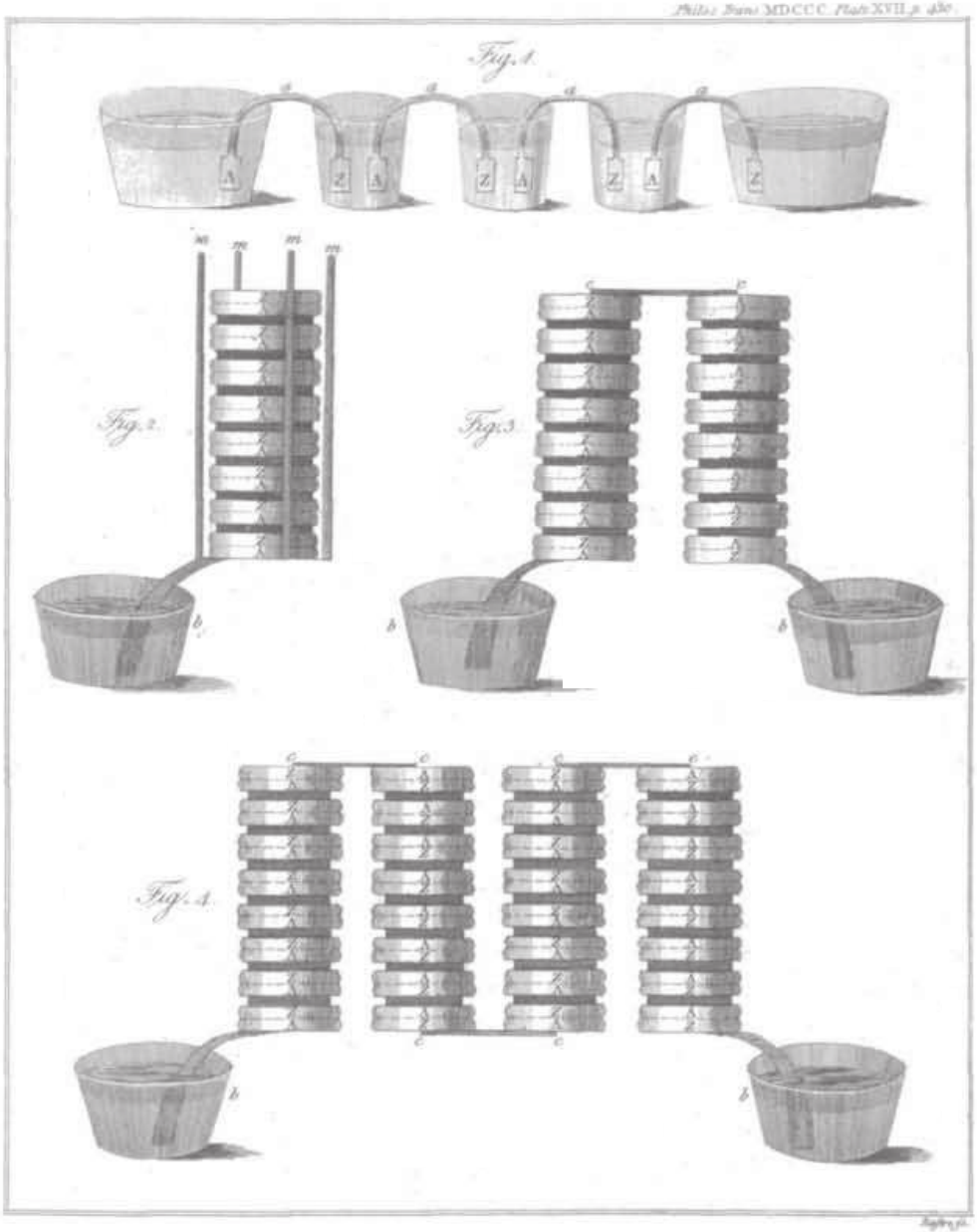

FIG. 2. Volta's illustration of the chain of cups and the pile or 'artificial electric organ' (n. 15).

the physical mechanisms underlying the electrical properties of the electric organ. That he believes the pile to be a realistic model of the *natural* organ is borne out by the criticism which appears, toward the end of the letter, of another model proposed by Nicholson, an English investigator. In that model metal plates were separated by glass discs to form a column, a multilayered structure of flat 'condensers' in series. His rejection of Nicholson's model is straightforward, namely, in the electric organ, made up 'of very thin discs placed one upon the other, . . . we cannot suppose that any of these laminae are of an insulating nature like glass, resin, silk, etc . . .' Rather, Volta goes on to point out, 'Every animal substance as long as it is fresh, surrounded with juices, and more succulent of itself, is a very good conductor.'

In this way Volta makes the use of conductors the *sine qua non* for a valid model of the electric organ, a condition he satisfies in his own model. It is amusing that at this juncture he does not trouble to ask himself if the natural organ indeed contains metals. The certain failure to find any trace of metals, had he made the attempt, might have aroused within him a sense of caution and a modicum of humility about invoking the artificial organ to explain the physical mechanisms underlying the natural electric organ. But there is not a shade of hesitation evident in his concluding paragraph:

> To what electricity then or to what instrument ought the organ of the torpedo or electric eel, &c., to be compared? To that which I have constructed according to the new principle of electricity, discovered by me some years ago, and which my successive experiments, particularly those with which I am at present engaged, here so well confirmed, viz. that conductors are also, in certain cases, exciters of electricity in the case of the mutual contact of those of different kinds, &c., in that apparatus which I have named the *artificial electric organ*, and which, being at bottom the same as the natural organ of the torpedo, resembles it also in its form, as I have advanced.

Thus we must infer that Volta believes he has solved the problem of animal electricity as displayed in the electric organ of electric fishes. But what has become of the original problem posed by Galvani of animal electricity in the nerve-muscle preparation? On this central issue Volta is silent save for a brief reference to one of his earlier communications in which he was 'obliged to combat the pretended animal electricity of Galvani and to declare it an external electricity moved by the mutual contact of metals of different kinds.' There seems no reasonable explanation for Volta's failure to pursue logically the question of the current-generating

properties of nerve and muscle. If he accepted the electric organ as a problem for inquiry, then he should have examined the nerve and muscle system. And while in previous communications he asserts that nerve and muscle are passive, in this letter he 'deals' with the problem by avoiding it.

Volta's truly brilliant discovery of the 'electromotive apparatus' subsequently illuminated many branches of physics by providing for the first time a stable and powerful source of continuous current, not to mention its overwhelming technological applications. Still, ironically, the dazzling outcome of the Voltaic 'pile' by emphasizing the phenomenon of metallic electricity served to distract physiologists from investigating one of the basic properties of biological tissue, namely, animal electricity. Some forty years were to pass before Matteucci[17]—not faltering as did Nobili earlier in 1828—established beyond doubt that a 'current of injury' was associated with a crushed nerve or muscle. This unquestionably was the source of current in Galvani's experiment without metals and was indeed the basis of that animal electricity which Volta so illogically asserted did not exist.

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17. Carlo Matteucci, 'Deuxième mémoire sur le courant électrique propre de la grenouille et sur celui des animaux à sang chaud,' *Ann. Chem. Phys.*, 1842, *6*, 331–339. See also Giuseppe Moruzzi, 'The electro-physiological work of Carlo Matteucci,' *Proc. Int. Symp. Hist. Neurol.* (Varenna, 30 Aug.–1 Sept. 1961) (Milano, 1963), pp. 139–147, and Giuseppe Moruzzi, 'L'opera elettrofisiologica di Carlo Matteucci,' *Physis*, 1964, *6*, 101–140 (pp. 115–118).